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Publication Date
2019-10-01

DOI
10.1016/j.jenvman.2019.06.095

Peer reviewed

How alternative urban stream channel designs influence ecohydraulic conditions

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Cite as: Anim, D. O., Fletcher, T. D., Vietz, G. J., Burns, M.J., & Pasternack, G. B. (2019). How alternative urban stream channel designs influence ecohydraulic conditions. *Journal of Environmental Management*, *247*, 242-252

https://doi.org/10.1016/j.jenvman.2019.06.095

ABSTRACT

Streams draining urban catchments ubiquitously undergo negative physical and ecosystem changes, recognized to be primarily driven by frequent stormwater runoff input. The common management intervention is rehabilitation of channel morphology. Despite engineering design intentions, ecohydraulic benefits of urban channel rehabilitation are largely unknown and likely limited. This investigation uses an ecohydraulic modelling approach to investigate the performance of alternative channel design configurations intended to restore key ecosystem functioning in urban streams. Channel reconfiguration design scenarios, specified to emulate the range of channel topographic complexity often used in rehabilitation are compared against a reference 'natural' scenario using ecologically relevant hydraulic metrics. The results showed that the ecohydraulic conditions were incremental improved with the addition of natural oscillations to an increasing number of individual topographic variables in a degraded channel. Results showed that reconfiguration reduced excessive frequency of bed mobility, loss of habitat and hydraulic diversity particularly as more topographic variables were added. However, the results also showed that none of the design scenarios returned the ecohydraulics to their reference conditions. This indicate that channel-based restoration can offer some potential changes to hydraulic habitat conditions but are unlikely to completely mitigate the effects of hydrologic change. We suggest that while reach-scale channel modification may be beneficial to restore urban stream, addressing altered hydrology is critical to fully recover natural ecosystem processes.

Keywords: Urbanization; Stream restoration; Channel rehabilitation; Hydraulic modeling; Stormwater; Hydraulics

1. Introduction

Urban landuse changes and especially stormwater management are widely recognized as a driver of major changes in stream ecosystems (Ladson et al., 2006; Fletcher et al., 2014). Well-documented changes includes substantial hydrological disturbance (characterised by increased frequency, magnitude and duration of peak flows) (Konrad & Booth, 2005), water quality disturbance (Brabec et al., 2002), as well as channel morphology degradation (Vietz et al., 2014), primarily driven by urban stormwater runoff (Walsh et al., 2012). These changes lead to ecological degradation (Walsh et al., 2005; Paul & Meyer, 2008). As a result, urban streams are targeted worldwide and there are increasing restoration measures employed by managers to curb the urban-induced impacts. These measures aim primarily to restore stream biodiversity and ecological function (Wohl et al., 2005; Bernhardt & Palmer, 2007).

Restoration of urban streams generally has two main levers: addressing the altered hydrology (Burns et al., 2013; Bell et al., 2016) or the degraded channel morphology (Roni et al., 2008; Chin & Gregory, 2009). Regardless of restoration strategy, addressing channel morphology degradation remains one of the most common motivations for undertaking stream ecosystem restoration (Findlay & Taylor, 2006; Jähnig et al., 2009; Palmer et al., 2014). This is particularly due to the negative impacts of physical degradation on the environmental and social values that urban streams provide (Elmqvist et al., 2015; Arnold & Toran 2018). As a result, a majority of management strategies target in-stream morphological reconfigurations despite their high cost (Montgomery, 2006; Bernhardt & Palmer, 2011; Hering et al., 2015).

Approaches to addressing urban stream channel changes have evolved from traditionally focusing on increasing channel stability and simplification in support of flood control and bank erosion protection, to now adopting morphological reconfiguration and hydraulic structure addition in support of improved biodiversity and ecosystem services (Bernhardt et al., 2005;

Muhar et al., 2016). For example, morphological naturalization, involving the introduction of specific instream landforms to have a more natural appearance is widely performed (Sear et al., 2000; Bernhardt & Palmer, 2011). This usually involves some form of modification of the longitudinal and cross-section of channel at reach-scale to improve topographic variability (Sear & Newson, 2004; Wheaton et al., 2004; Pasternack, 2008). These are often done to create morphological complexity assumed to have the potential to promote ecological improvement and biodiversity (Chin & Gregory, 2009; Palmer et al., 2010). This assumption is hinged on research showing that biota richness and diversity and channel topographic heterogeneity are positively correlated (Brown, 2003; Violin et al., 2011).

However, in recent times, concerns over the performance of channel reconfiguration actions to achieve restoration goals have been raised (Miller & Kochel, 2010; Wohl et al., 2015). Notably, studies evaluating post-restoration projects have reported they usually yield little or no ecological benefits (Gurnell et al., 2007; Kondolf et al., 2007; Baldigo et al., 2010; Bernhardt & Palmer, 2011; Kim et al., 2019), especially for streams draining substantially urbanized catchments (Walsh et al., 2012). What is missing from the literature is a clear link between driving topographic and hydrologic factors and resulting ecological outcomes. The missing link is the domain of ecohydraulics, which explores the mechanisms (herein the interactions between flow regimes and the channel morphology) and describes hierarchically nested aquatic and riparian biotic phenomena (Casas-Mulet et al., 2016; Kuriqi & Ardiçlioğlu, 2018).

To get at the ecohydraulics involved in urban stream syndrome, Anim et al. (2018a) quantified the hydraulic conditions in urban streams (with altered hydrology) and demonstrated that they are substantially altered compared to a reference ‘natural’ stream. The urban stream subjected to altered hydrology experienced significant increased bed disturbance (bed particle mobilization), decreased refuge habitat and decreased hydrological connectivity (Anim et al., 2018a). Whilst most studies evaluating the performance of the urban stream channel reconfiguration outcomes do not report the mechanism leading to failure, the findings of Anim et al. (2018a) highlight the real issue behind the syndrome itself and restoration failure could be the altered ecohydraulic conditions. This could be a limiting factor for the lack of desired ecological improvement. Indeed, it is argued that restoration strategies should consider hydrogeomorphic process that are directly linked to the ecosystem functioning needs of the target stream (Wohl et al., 2015). It is important that the channel rehabilitation efforts achieve the hydraulic habitat conditions that will promote ecological benefits. Hydraulic conditions influence biota and ecosystem functioning and it is often used to speculate the mechanism that influence ecological health of streams (Jowett, 2003; Mérigoux & Dolédec, 2004; Clark et al., 2008; Turner & Stewardson, 2014).

In light of the failures of current stream engineering practices, research has called for a move away from channel-based restoration approach towards addressing the root causes that fundamentally alters the hydrology and sediment supply (Walsh et al., 2012; Vietz et al., 2016). However, while addressing the root causes of urban stream syndrome is certainly important, Anim et al. (2018b) found that once the channel morphology has been substantially degraded, mitigating altered hydrology alone cannot return 'natural' channel ecohydraulics. They suggested that in such cases, opportunities for channel morphologies rehabilitation may need to be considered hand-in-hand with addressing catchment drivers (Anim et al., 2018b).

In this study, we build on recent findings to explore the research question: 'How do alternative channel rehabilitation designs using an increasing number of oscillating topographic variables impact instream hydraulic conditions?' We explored the effectiveness of different channel reconfigurations common to emerging stream channel rehabilitation design concepts (Brown et al., 2016) on modifying ecologically relevant hydraulic conditions. For each reconfiguration, we used two-dimensional (2D) hydraulic modelling to quantify changes in bed mobility, hydraulic diversity and habitat availability. We demonstrate that rehabilitation could support ecosystems through reinstating appropriate hydraulic conditions by means of channel modification with linked oscillating topographic variables, in addition to modifying flow. By focusing on how channel morphology relates to hydraulic conditions at an ecological relevant scale, the opportunities for stream rehabilitation could be made more strategic.

2. Methods

2.1. Experimental design

The modelling approach was fourfold (Figure 1). First, we adopted pre-existing case-study stream reaches selected to physically represent and compare an urban and natural (reference) setting (with representative hydrology and channel form). Second, a set of synthetic stream corridor Digital Terrain Models (DTMs) was generated by applying the synthetic river valley procedure of Brown et al. (2014) using channel parameters data from both real reaches. From an initial simple synthetic urban channel reach, four different DTMs were created representing channel reconfiguration designs with incrementally more variables (i.e., depth, width, and centreline) given natural undulations. These incrementally reconfigured topographic surfaces of the degraded urban channel characterised different degrees of reach-scale morphological complexity to mimic the natural 'reference' condition at the reach-scale. Note that for this study, the channel design focused on reach-scale design excluding local hydraulic structures. There are too many possible structures one might add to the test scenarios as well as infinite options for placement position, size, and orientation. That would require a comprehensive study of its own, which was beyond the scope of this study. Third, a 2D hydraulic model was used to simulate ecohydraulic impacts of each channel scenario. Finally, the temporally varying hydraulic performance of each reconfigured channel was quantitatively evaluated using metrics of known ecological relevance that evaluates the bed disturbance, habitat value and ability to produce hydraulic diversity. We tested how closely each hydraulic metric deviated from the urban case after channel reconfiguration. These steps are described in more detail in the following sections.

2.2. Study-site settings

The study sites setting used in here were segments of the Cardinia Creek length in the Cardinia Shire catchment, south-eastern Melbourne, Australia investigated in previous study by Anim et al. (2018b). The two reaches have distinguished hydrology and morphology, physically representing an urban and natural settings. The urban reach drains an urbanized section of the catchment that retains about 40% forest/tree cover, with the remainder of the surface area cleared for urban development. Some 7% of the total catchment area is impervious with half of the impervious surfaces connected to the stream through stormwater drainage systems. This suggests that this reach will be significantly influenced by the catchment land use and upstream drainage area (Burns et al., 2012). The natural reach drains 50% forest/tree cover and 43% pasture/grassland cover. 4% of the catchment is covered by impervious surfaces, with only 0.1% draining directly to the stream suggesting minor hydrological disturbance (Walsh, 2004). Both sites have similar rainfall pattern, averaging ~950 mm/year annually, well distributed over the catchment, with higher rainfall in winter-spring (Anim et al., 2018a).

2.2.1. Study reach topography

The natural reach has an intact and complex naturally meandering, pool-riffle channel morphology with a sand-gravel bed and lateral benches. The urban reach has an incised (deepened and widened) and simplified (homogenous) sand-gravel plane bed channel morphology with less complexity both in cross-profile and planform. Existing field data from a detailed channel survey of each reach provided typical reach-average channel geometric elements including bankfull depth (H_{bf}), width (W_{bf}), slope (S) and a representative median particle size (D_{50}).

2.2.2. Hydrological regime

Continuous streamflow gauge records (January 2008- December 2016) providing a good representation of a typical dry, normal and wet water year conditions were available for the study reaches. These were that used by Anim et al. (2018b) (Figure 2). The urban streamflow regime is characterised by an increased frequency of flashy (including higher peak magnitude, frequency and short-lived) flows occurring especially during winter periods and lower baseflows during summer compared to the natural. This reflected a typical urban stream hydrological regime influenced by stormwater runoff from connected impervious surfaces contributing flows (Burns et al., 2012).

2.3. Synthetic test channel morphology

Archetypal stream channel morphology were created using an open source "RiverBuilder" R package (version 0.1.0) which is an emerging technique of synthesizing channel topography for science and engineering application (Arroyo & Pasternack, 2017). RiverBuilder as a practical river design tool is based on the synthetic river valley framework of Brown et al. (2014) that renders a DTM from user-selected geometric functions describing the topographic variability at reach and subreach scales. Herein we provide only the equations used to create the specific DTMs used in this study.

2.3.1. Channel design parameterization

RiverBuilder allows synthetic channel topography to be developed based on the following reach-average input dimensions: $\mathrm{H_{bf}}$, $\mathrm{W_{bf}}$, S and $\mathrm{D_{50}}$, floodplain width and slope. These inputs were computed and scaled from surveying the case study reaches (Table 1). From these inputs, user-defined subreach-scale topographic variability can be added using combinations of geometric functions, $\mathrm{f(x_i)}$ in RiverBuilder. There is no limit to how many different functions may be added together to represent the longitudinal structure of an individual geometric variable. The subreach variability for each channel was designed using Eq (1) and (2) such that the local bankfull width and bed elevation of thalweg was calculated as:

$$W_{bf}(x_i) = \left(\overline{W_{bf}} f(x_i) + \overline{W_{bf}}\right) \tag{1}$$

$$z_t(x_i) = \left(\overline{H_{bf}} f(x_i) + \overline{H_{bf}}\right) + S(\Delta x_i) + Z_d \tag{2}$$

where $W_{bf}(x_i)$ and $z_t(x_i)$ are the bankfull width and local bed elevation at position x_i respectively, and Z_d is the user-defined datum. There are many possible functions, $f(x_i)$ provided in RiverBuilder including linear, trignometric and Perlin noise that can be used to describe the channel variability and for each an infinite variety are obtainable depending on chosen parameters (Brown et al., 2014). Herein, the general sinusoidal model was used to achieve the variability of W_{bf} and Z_t about the reach-averaged values by a control function $f(x_i)$ nested in Eqs. 2 and 3 as

$$y(x_i) = a_s \sin(b_s x_r + \theta_s) \tag{3}$$

where y_i is the dependent control function values, a_s, b_s, and θ_s are the amplitude, angular frequency and phase for the sinusoidal competent and x_r is the Cartesian stationing in radians (Brown et al., 2014). The channel reach-average and variability geomorphic attributes used in the design of the synthetic DTMs of each investigate channel configurations are shown in Table 1.

Table 1.Reach average and control functions parameters used for each designed channel scenario.

Reach channel parameters		**Urban**	$\boldsymbol{Urb_W}$	$\boldsymbol{Urb_D}$	$\boldsymbol{Urb_{W+D}}$	$\boldsymbol{Urb_{W+D+M}}$	**Natural**
Bankfull width (m)	W_{bf}	6.50	7.29	6.50	6.47	6.50	4.2
Bankfull depth (m)	H_{bf}	0.97	0.90	0.89	0.92	0.75	0.6
Median particle size (m)	D_{50}	0.006	0.006	0.006	0.006	0.006	0.006
Channel Slope (%)	S	0.002	0.002	0.002	0.002	0.002	0.001
Vertical datum (m)	Z_d	1000	1000	1000	1000	1000	1000
Channel length (m)	L_X	150	150	150	150	150	150
Sinuosity	S_L	1.0	1.0	1.00	1.00	1.20	1.30

Variability parameters		**Urban**	$\boldsymbol{Urb_W}$	$\boldsymbol{Urb_D}$	$\boldsymbol{Urb_{W+D}}$	$\boldsymbol{Urb_{W+D+M}}$	**Natural**
Bankfull width	a_s	0	0.25	0	0.25	0.25	0.25
	b_s	0	3	0	3	3	3

	θ_s	0	0	0	0	0	0
Bed elevation	a_s	0	0	0.25	0.25	0.5	0.5
	b_s	0	0	3	3	3	3
	θ_s	0	0	0	0	0	0
Planform	a_s	0	0	0	0	0	10
	b_s	0	3	3	3	3	1
	θ_s	0	0	0	0	0	0
Floodplain outline	a_s	0	0	0	0	5	0.25
	b_s	0	0	0	0	1	2
	θ_s	0	0	0	0	3.14	3.14

2.3.2. Channel design configurations.

The synthetic channel of the urban and natural reach of the case-study settings was first developed using the reach and sub-reach channel parameters. From the single synthetic channel reach developed for the urban reach (Urb), four different DTMs were created representing channel restoration design with variability that spans the full domain of bed and width undulation combinations (Table 2). Here, each channel reconfiguration created is analogous to some typical channel designs employed by practitioners to enhance channel morphology. For example, bed undulations are commonly used without width undulations. Meanwhile, width undulations are increasingly recognized as important hydraulic controls and are beginning to show up in urban stream restoration projects. The first channel reconfiguration scenario is the urban channel with added width variation only (Urb_W). The second scenario is urban channel with added depth variation only (Urb_D). The third is urban channel with both width and depth variation (Urb_{W+D}). In this case, the two variations are linked with a positive geomorphic covariance structure (i.e. high, wide riffles and narrow, deep pools) typical of self-sustainable riffle-pool systems (Brown & Pasternack, 2017). The fourth is urban channel with positively co-varying width and depth undulations as well as meandering (sinuosity) (Urb_{W+D+M}). In this study, the same reach-average input values were used for the pre-restored and restored configurations of the urban channel. In additions, bed material is kept uniform for all channels. See Supplementary Material for full topographic surfaces of designed synthetic channels.

Table 2. Channel morphological designs scenarios investigated in this study. Channel archetype are in order of morphological complexity (from least to more complex) condition compared with the reference 'natural' channel condition. Subscripts W, D and M represents width, depth and meander channel features respectively.

Channel archetype Scenario	**Description and geomorphic elements included**	**Design conceptualization analogous**
urban channel (Urb).	Semi-confined uniform (with no width and depth undulation) channel	Channelized and greatly morphologically altered channel with uniform cross-sections and longitudinal slope
$\boldsymbol{Urb_W}$	Urban channel with only width undulation	Approach analogous to local widening to allow channel movement within limited area
$\boldsymbol{Urb_D}$	Urban channel with only depth undulation	Approach analogous to reconfiguring incised channels with undulating streambed resembling pool-riffle sequence which is expected to offer higher degree of ecological function

$\boldsymbol{Urb_{W+D}}$	Urban channel with both width and depth undulation	Approach comparable to local widening with undulating streambed similar to pool-riffle sequence
$\boldsymbol{Urb_{W+D+M}}$	Urban channel with both width and depth undulation and meanders	Naturalised morphology, close to typical natural channel (channel with more varying topographic landforms)
Natural channel ($\boldsymbol{Nat}$).	Bed and width varying with meanders and lateral benches	complex varying cross-sections, sinuous pool-riffle channel morphology with lateral benches, local topographic perturbations

2.4. 2D Hydraulic modeling

2D hydraulic modeling was undertaken using the TUFLOW Classic model (Build 2016 0-3_w64) that solves the full 2D, depth-averaged momentum and continuity equations for free surface flow equations. TUFLOW has been extensively used to study variety of hydrogeomorphic processes and allows a robust 2D modeling of rivers with complex flow patterns which makes it a suitable computational tool for complex hydraulic characterization (Syme, 2001). From the DTM data points generated for each channel by RiverBuilder, a square grid computational mesh was constructed with 150 longitudinal nodes spaced at 0.3 m. The default TUFLOW Smagorinsky viscosity was used for turbulence closure with coefficient value of 0.5 and constant value of 0.005 m^2/s suitable for shallow waters (Anim et al., 2018a). A Manning's coefficient n value of 0.04 was used, representing typical unvegetated coarse-particle surface roughness (Arcement & Schneider, 1989).

Model simulations used discharge (Q) as input and flow stage as the downstream boundary condition. Discharge and corresponding flow stage were estimated using Manning's equation based on representative cross-sections of the synthetic DTMs (Table 2). Bankfull stage and wetted perimeter were calculated manually from the cross-sections and cross-sectional area determined using the parabolic approximation. Discharge ranged from 0.1-1.0x the bankfull flow (Q_{bkf}) stage. The water surface elevation (WSE) at which flow overtops the banks was the Q_{bkf} stage. Model outputs include hydraulic rasters of depth-averaged velocity in the direction of flow, water depth, bed shear stress (τ_b) and WSE. ArcGIS (Esri ArcGIS desktop 10.2) was used to process and analyze these outputs to evaluate each investigated channel configuration. Typical of published exploratory numerical modeling studies, calibration of bed roughness or eddy viscosity was not possible as the study uses numerical models of theoretical channel archetypes in purely exploratory mode (Pasternack et al., 2008; Brown et al., 2016; Lane et al., 2018).

2.5. Ecohydraulic metrics

The study explored three ecologically relevant hydraulic characteristics that have been mechanistically linked with stream ecosystem functions: (i) channel bed disturbance that impacts bed particle mobilization and disturbance of benthic dwelling biota (Gibbins et al., 2010); (ii) hydraulic diversity – Hydro-Morphological Index of Diversity (HMID); and refuge habitat availability - Shallow Slow-Water Habitat (SSWH). They were quantified using related hydraulic metrics including near-bed Shield stress as indicators of bed mobility, a measure of flow velocity and depth heterogeneity reflecting the reach hydraulic diversity and a measure of physical habitat area that determines the availability of slow and shallow depth water respectively. These hydraulic metrics were determined from the raster outputs of the hydraulic model calculated using python decision tree in ArcGIS over defined threshold bounds.

2.5.1. Bed disturbance

Frequent bed disturbance increases channel instability and degradation and also drift of biota that lives in them (Hawley et al., 2016; Lobera et al., 2017). Non-dimensionalized bed shear stress, Shields stress (τ^*) was used to quantify and compare each channel for their bed mobilization potential. This was estimated in each grid cell of the model grid cell as:

$$\tau * = \frac{\tau_b}{D_{50}(\gamma_s - \gamma_w)} \quad (4)$$

where and γ_s and γ_w are the unit weight of bed particle and water respectively and τ_b is bed shear stress. Herein, a critical entrainment threshold (τ_c^*) of 0.045 (Lisle et al., 2000; Sawyer et al., 2010) was used to differentiate the portions of the channel bed that indicate mobility ($\tau * > \tau_c^*$) and stable ($\tau * < \tau_c^*$).

2.5.2. Hydraulic diversity

The channel diversity of flow velocity and depth is well recognized as an essential element of ecosystem health supporting various life history strategies of biota (Verberk et al., 2008; Rosenfeld et al., 2011). We estimated this hydraulic heterogeneity using the hydro-morphological index of diversity (HMID) developed by Gostner et al. (2013). HMID quantifies the overall hydraulic diversity in the channel for a given discharge based on the reach-scale coefficient of variation (CV) of flow velocity (*u*) and water depth (*d*) as:

$$HMID_{channel} = (1 + CV_u)^2 + (1 + CV_d)^2 \quad (5)$$

where $CV = \sigma/\mu$, σ and μ are the standard deviation and mean value respectively. HMID values where classified to reflect by Gostner et al. (2013) such that HMID <5 assumes low diversity; 5 < HMID < 9 assumes medium or transitional diversity; HMID > 9 assumes high diversity.

2.5.3. Refuge habitat availability

SSWH is critical to biota that depend on them as refugia particularly during flash flood as well as serving as rearing and breeding habitat, and promoting organic matter retention (Schiemer et al., 2001; Vietz et al., 2013). Herein, the relative refuge habitat availability was examined by estimating the SSWH area. SSWH was calculated from the flow depth and velocity model output using an ArcGIS python script that processes water depth and velocity raster outputs to locate cells with joint velocity and depth values of 0-0.2 m/s and 0-0.3 m respectively. This depth and velocity criteria is reported to be preferred by fish (Milhous & Nestler, 2016) and benthic macroinvertebrates (Shearer et al., 2015) in streams.

2.6. Hydraulic response analysis

To initiate a comparative analysis among the different channel configurations, first a functional relationship was developed for the range of simulated flows for each hydraulic metric. This relationship was then integrated with the hydrological time series to achieve hydraulic metric time series representing the temporal pattern of the hydraulic response under each channel. The urban hydrological time series was parsed into the functional relationship for the urban and reconfigured urban channel scenarios. Similarly, the natural hydrological time series was parsed into that of the natural channel scenario. Then by quantitatively characterizing and comparing the temporal hydraulic variation, we evaluated the relative influence of the channel reconfiguration from the pre-restored condition towards the natural conditions. The statistical analysis of the time series of each metric (mean daily) examined the relative percent change of the various aspects of the hydraulic patterns: magnitude, duration and frequency as key element of the hydraulic template for each scenario. The analysis also accounted for the hydraulic metric change with flow in relation to defined thresholds. In this study, hydraulic metrics were considered only for flows up to bankfull.

3. Results

Hereinafter, the use of “reference case” and “urban case” scenarios refers to hydraulic conditions in (i) the natural channel under natural hydrological regime and (ii) unrestored urban channel under urban hydrological regime respectively.

3.1. Bed disturbance

Results show a general trend of increase of bottom shield stress with increasing discharge with a rapid increase in the Shield stress values as flow increased under the two urban case scenarios with no bed undulation (Urb and Urb_W) (Figure 3a). The results show that the maximum bottom shield stress per unit flow decreased as the channel topographic variability increased. The bed particle mobility threshold was applied to the shield stress results for each reach to determine the proportion of channel bed area with Shield stress higher than the threshold of mobility (Figure 3b). It indicates that the increasing number of topographic variables made to undulate invariably decreased the areas of channel bed experiencing mobility particularly for Urb_{W+D+M} and the natural channel morphology. This suggests that morphology with at least one undulating geometric layer for each topographic variable nested on top of the basic reach-scale uniform channel template potentially decreased the mean shear stress as flow increases. This phenomenon was most relevant at discharge stages over $0.5Q_{bkf}$. As discharge exceeds $0.6Q_{bkf}$, urban channels with only width or depth undulation have less control over bed mobilization and the whole channel trends towards mobility, similar to the urban channel. For such high flows, adding both width and depth variability substantially reduced the wetted bed area experiencing mobility. For these channels, almost 45% of the bankfull channel provided undisturbed benthic area compared to the plane bed channels.

In addition, temporal variability of daily shield stress was greater in the urban plane channel bed compared to the pool-riffle bed for the studied hydrological period (Figure 4). This was however dominated by high occurrences of daily Shield stress above threshold for mobility ($\tau * > 0.045$) with a median value of 0.042 and 0.038 for Urb and Urb_W respectively. This indicated temporal persistent of unstable channel bed. This frequently occurring case of mobility was substantially reduced as the topographic complexities of the urban channel increased particularly. In contrast, temporal variability of daily shield stress for the natural channel scenario showed incremental period of below mobility threshold Shield stress values with median of 0.026 indicating comparably stable bed.

3.2. Hydraulic diversity

The greatest different between the channel scenarios investigated occurred at low flows (< $0.3Q_{bkf}$), where highest HMID values were observed (Figure 5) and decreased with increasing flow (>$0.5Q_{bkf}$). The low-to-peak flow loss of hydraulic diversity showed the natural channel maintaining high HMID values where diversity was within moderate to high class for flows up to $0.7Q_{bkf}$. In contrast, HMID values were only within moderate values for urban channel (Urb) even at low flows, which plummeted to low diversity (HMID<5) as flow exceeds $0.4Q_{bkf}$. During the low flows, HMID was almost twice as high in the pool-riffle channel types compared to the plane bed channels. Whilst HMID decreased with increasing flow, pool-riffle channel with meandering (Urb_{W+D+M}) with more gradual side slopes showed some increases in HMID as flow exceeded $0.6Q_{bkf}$.

The HMID was lowest in the channel scenarios with no bed undulation (Urb and Urb_W) (Figure 6), with a narrow range. For all flows, mean velocity in these channels were remarkably higher than the pool-riffle channels. In contrast, the range of velocity and depth was widest in the pool-riffle channels with lower minimum and higher maximum values across all modelled flows. This resulted in higher depth range and CV particularly for Urb_{W+D} and Urb_{W+D+M}. The plane channel bed morphologies showed the least temporal persistence of high hydraulic diversity (HMID>9) with a median HMID value of 4.8 and 5.5 for scenarios Urb and Urb_W respectively. The limited temporal persistence of high hydraulic diversity was improved by inclusion of both width and depth variation in the channel (Urb_{W+D} and Urb_{W+D+M}). These channels mostly experience medium and high diversity particularly for Urb_{W+D+M} with a median value of 7.6. The natural case showed temporal persistence of high hydraulic diversity.

3.3. Refuge habitat availability

Similar trend of changes to SSWH availability with flow was observed for all channel scenarios (Figure 7a and 7b). SSWH area was high at low flows (below $0.3Q_{bkf}$) occupying more than 50% of total wetted area in the reach. The gradually changing morphological relief of the natural channel maintained more than 50% of total SSWH patch up to $0.5Q_{bkf}$ and decreased steadily as flow increased. The plan bed channels (Urb and Urb_W) inundated to higher flow depths and velocities as flow increased, thus the SSWH area plummeted at rapid rates. SSWH area was higher in the urban channel with only depth variation (Urb_D) than plane bed morphology at flows up to $0.5Q_{bkf}$, beyond which they were nearly equivalent. For each modelled flow, an average of 15% increase of the SSWH area was observed when both width and depth variability (Urb_{W+D} and Urb_{W+D+M}) was added to the plane bed channel morphology (Figure 7b). Here, the proportion of the reach occupied by SSWH area was at least 2x higher than the plane bed channels.

The frequently occurring high flows (>0.6Qbkf) in the urban hydrology reflected in the high temporal persistence of smaller SSWH areas (< 300m^2/150m) in the urban channels particularly for the plane bed channels. A median value of 245.2 m^2/150m and 264.5 m^2/150m was observed for Urb and Urb_W respectively. This was however greatly improved for the pool-riffle bed with width variation channel morphologies, with about 50% increase in the median SSWH values compared to confined plane bed channel. High temporal persistence of larger SSWH area (>500m^2/150m) was observed for the natural channel with a median value of 456.3m^2/150m. This reflected a natural complex morphology engaged by the long duration-low magnitude flows in the natural hydrological regime with reduced frequency of high flows.

4. Discussions

4.1. Hydraulic performance of channel reconfiguration scenarios

Comparison of quantitative hydraulic metrics for each of reconfiguration scenario reveals two general points. Firstly, simple channel form, defined as a uniform, U-shaped, single-threaded channel with no width, depth, or centreline variation, leads to simple hydraulics. The simplified (homogenous) channel topography, typical of many urban settings, deleteriously alters hydraulic patterns. This is perhaps expected but not necessarily well proven with data as provided in this study. Secondly, channel forms with increasingly more geometric variables having undulations yield to more increasing better performing hydraulics. The more geometric elements were added to the channel up to the full patterning of depth, width, and centreline structures, the less sensitive the channel was to an altered urban flow regime highlighting the importance of spatial diversity in channel morphology for supporting stream ecosystem health (eg., Escobar-Arias & Pasternack, 2010; Schwartz et al., 2015; Lane et al., 2018a). This does not mean that adding infinitely more geometric functions to any one variable or by adding many more undulating geometric variables will make the conditions better than what was studied; it will take more research to figure out what is optimal for each river setting. Channels with naturalized geometric oscillations coherently phased to yield requisite morphodynamic processes dynamic morphologies have a better chance of minimizing the influence of altered hydrological regime on the hydraulic conditions. Thus, making biota less prone to rapid temporal fluctuations than an unrestored reach.

Designing the urban degraded channel to include a pool-riffle sequence, plus some undulations in width or sinuosity, provides greater opportunity for improved hydraulic conditions. For instance, in addressing the bed mobility rate, Schwartz et al. (2015) reported that restoring riffle-pool structure promotes shear stress reversals between low and high flows as well as high flow acceleration and deceleration between pools and riffles (eg., Brown & Pasternack, 2017). This is essential for spatiotemporal heterogeneity of the hydraulic characteristics of the flow such as water depth, flow velocity and turbulence, to promote habitat creation and quality (Clarke et al., 2003). While predicting the 'optimal' channel morphology for urban restoration design is beyond the scopes of the current study, our results suggest that the hydraulic conditions can be significantly modified with even minor width and depth undulations and sinuosity patterns. Brown and Pasternack (2014) reported that multiple physical mechanism process occurs as modulated by the interactions of the flow hydrology with complex channel topography. It is thought that channels with different topographic features steer the flows in such a way that different features turn on and off to create diverse patterns of hydraulic conditions (Strom et al., 2016). This will potentially support sustaining spatial and temporal hydraulic patterns at levels below the threshold for certain processes (eg., Gostner et al., 2013; Vanzo et al., 2016; Lane et al., 2018a). For instance, Anim et al. (2018a) found that complex topographic variability decreased areas of channel bed subjected to high hydraulic stress for bed particle movement even with increasing flows.

To summarize, topographic dynamic channels may support fundamental physical process at appropriate levels even under altered urban hydrology characterized by increased frequency, magnitude and volume of storms flows. It is however worth noting that *appropriate* here is intended to imply reduction in excessive frequency of bed disturbance or scouring rates, loss of physical habitat and hydraulic diversity.

4.2. Can modifying reaches reverse catchment-scale degradation sources

Results demonstrated that reconfiguring channel morphology close to natural form can help to accommodate changes to altered flow. Doing so restores ecologically relevant hydraulic conditions. For example, refuge habitat availability between simple channels and the most complex improved by 32%. Reinstating bed diversity increases hydraulic diversity by 21%, with a further 20% increase when sinuosity was added. Bed disturbance can be decreased by 45% (see Table 3). Further improvements could potentially be achieved by combinations of high-undulations and geomorphic covariance structures and through the addition of sub-reach-scale in-stream features such as alluvial benches, boulder clusters, wood structures, alluvial steps.

However, when compared to the reference case scenario, the hydraulic patterns of modified channels under degraded hydrology were still not returned to a fully 'natural' condition. In this light, we argue that attempts to restore extensive morphological features is likely to be ineffective when a counter fundamental problem like dramatically fluctuating flows remains unaddressed. Given that the urban hydrology is characterised by increased frequency and magnitude of peak flows (Walsh et al., 2012), the efficacy of increasing morphological variability to ensure high diversity hydraulic habitat will be affected.

Only 7% of the total catchment area of the urban site is impervious with about half of the impervious surfaces connected to the stream via stormwater drainage systems. As urbanization progresses and intensifies, the proportion of connected imperviousness is expected to increase, exacerbating modifications to the flow regime (Jacobson, 2011; Burns et al., 2012). Modifying an urban channel does nothing to address this fundamental driver of flow regime and sediment supply that degrade a stream corridor over years to decades. If the fundamental driver is not addressed, then downstream actions cannot sustain themselves. This is essential so that incorporated forms are functional beyond their initial construction and propagate through to ecological functions. We propose it is possible that optimal ecosystem restoration of urban streams with demonstrable ecological benefits could be achieved if considerable effort and some thinking outside of channel-based approaches are made as suggested by Vietz et al. (2016).

Table 3. Average percentage increase (+) or decrease (-) of the explored hydraulic characteristics for flows above 0.5Qbkf for each channel scenario. Values are relative to what was predicted in the unrestored urban channel (Urb).

Channel scenario	**Bed disturbance (Shield stress) (%)**	**Hydraulic diversity (HMID) (%)**	**Refuge habitat (SSWH) (%)**
Urban channel with only width variation ($\mathrm{Urb_W}$)	- 7	+ 12	+ 4
Urban channel with only depth variation ($\mathrm{Urb_D}$)	- 12	+ 21	+ 10
Urban channel with both width and depth variation ($\mathrm{Urb_{W+D}}$)	- 37	+ 30	+ 21
Urban channel with both width and depth variation and meander ($\mathrm{Urb_{W+D+M}}$)	- 45	+ 41	+ 32

4.3. Implications and opportunities for restoration of urban streams

Results showed that the addition of naturalized undulations to depth, width, and centreline position, yield more diverse hydraulics that approach natural conditions. This supports the increasing recognition of structurally organized and harmonically coherent spatial diversity as a central feature of aquatic systems to promote the physical template within which ecosystem processes such as sediment transport, nutrients dynamics can occur at natural rate (Clarke et al., 2003; Escobar-Arias & Pasternack, 2010; Lane et al., 2018). In addition, it overlaps with the general consensus that the more diverse the channel the greater the ecological benefit expected (Chin & Gregory, 2009; Bernhardt & Palmer, 2011; Beagle et al., 2016). The lack of in-stream structures in this study leaves open the possibility that further improvements are possible. However, such features tend to be more prone to collapse and work best when fed and created through natural processes, whereas re-configuring the reach-scale structure is extremely different to obtain passively.

Key ecosystem functions associated with key stream health integrity are controlled by the mutual interplay between morphology and the hydrological regime, so channel form and flow inputs are critical (Clarke et al., 2003; Brown & Pasternack, 2014). In this regard, solving one may not necessarily address the other. While managing of other aspects of land use and channel form might be required or beneficial for an urban stream restoration, it is certain restoring altered flow regime is a prerequisite to have a chance to fully recover natural ecosystem. We propose a practicable and comprehensive stream restoration approach requires outside stream perspectives, where a broader catchment-scale management practices that addresses the source of ecosystem degradation are critically considered. Such an approach requires a consideration of flow-regime stormwater management and the application of strategies at or near the source to meet required flow regime target (Burns et al., 2014; Fletcher et al., 2014). This is in line with recently emphasized process-based restoration that expresses a broader effort of addressing the root cause of ecosystem degradation along a recovery trajectory (Beechie et al., 2010; Walsh et al., 2016). The present study presents to urban stream managers a methodological design measures that is underpinned on ecohydraulic principles. The hydraulic and geomorphic modelling approach used can be a template to understand the optimal combination of flow and morphological restoration.

Legacy impacts may mean separate modification of channel form and flow is required, to give managers flexibility particularly when both ecological and social values of the aquatic ecosystems are to be considered (Jacobson & Galat, 2006).

4.4. Uncertainties and applicability of study approach

This study used an emerging technique of synthesizing channel morphology for science and engineering applications. The use of synthesis of earth landforms is a valuable element of scientific research, because it gives the opportunity to test conditions that may not be accessible in nature such that underpinning causalities can be explored (Richards, 1978; Brown et al., 2014). While this technique is promising in replicating general topographic characteristics at reach scales, it also has some limitations. This study incorporated general channel attributes scaled by generic reach-average geomorphic elements of case-study stream reaches. This could present some uncertainties to the synthesized morphologies. The chosen geomorphic attributes for modification are only some possible elements. Further, the use of a simple sinusoidal variability control function (Eq. 3) with only one term per variable means the width and depth variations were symmetrical which is presumed to be likely asymmetrical in the real stream. River Builder is capable of generating far more sophisticated undulations though harmonic combinations and blending non-trigonometric functions. More research is needed to know what functions are needed for each topographic variable.

In addition, the primary hydrological input into the developed hydraulic model of each tested scenario was the stage-discharge relationships, manually computed from cross-sections of the synthetic channels. While real hydrological time series of the case-study stream reaches were used in the temporal analyse of the hydraulic performance, the use of hydrological values scaled to synthetic DTMs in the hydraulic modeling present some data input uncertainties. We emphasize that these scaled values are estimates and care should be taken when using as utmost targets to inform management. Research is on-going to understand hydrological baseline archetypes and their scaling in different channel archetypes (Lane et al., 2018b). Finally, this study also did not consider other key critical aspects of stream ecosystem such as water chemistry, temperature, substrate composition.

5. Conclusions

This study used a 2D ecohydraulic modeling framework to evaluate the performance of alternative channel design configurations which aimed to restore an urban-impacted stream channel. The analysis assessed the ability of the explored configurations to restore in-stream hydraulics close to their natural conditions by comparing their ecologically relevant hydraulic characteristics.

The results illustrated that achieving channel morphological variability in a degraded urban channel could help mitigate the influence of altered hydrological regime on the hydraulic conditions. As the variability increased, some improvement in the hydraulic conditions in terms of minimized bed mobility rate, reduced hydraulic diversity and habitat availability loss was observed. The reconfigured urban channel with bed diversity and sinuosity showed the most resilient to hydrological fluctuations offering 45% decreases in bed disturbance, 32% increases in habitat availability and 41% increases in hydraulic diversity per unit flow, compared to the unrestored channel. However, the results suggested restoring a more natural flow regime management is required, if natural hydraulic conditions are to be achieved. We argue that without the flow regime being addressed, restoring channel-based restoration attempts is likely to be hindered by the countering effect of increased magnitude, frequency and duration of disturbance flows. An integrated approach considering both reach-scale intervention and addressing catchment scale drivers of channel form is thus required.

Acknowledgments

This work was funded by a University of Melbourne Research Scholarship and undertaken through the Waterway Research Practice Partnership, supported by Melbourne Water. T.D Fletcher was supported by ARC project FT100100144 during part of this work. D. Anim was supported by the Albert Shimmins Fund from the University of Melbourne during part of this work.

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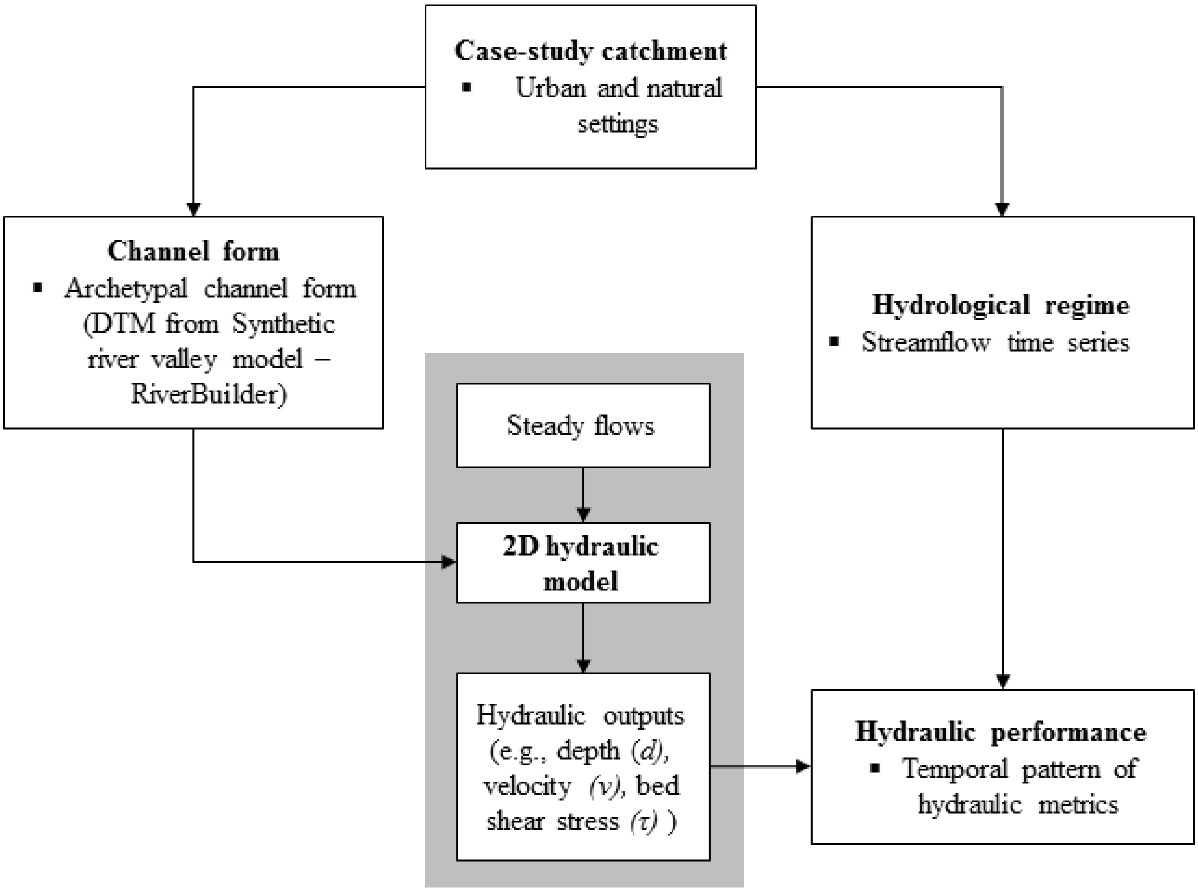

Figure 1. Modelling approach steps used to quantify the hydraulic impacts of each investigated channel configurations.

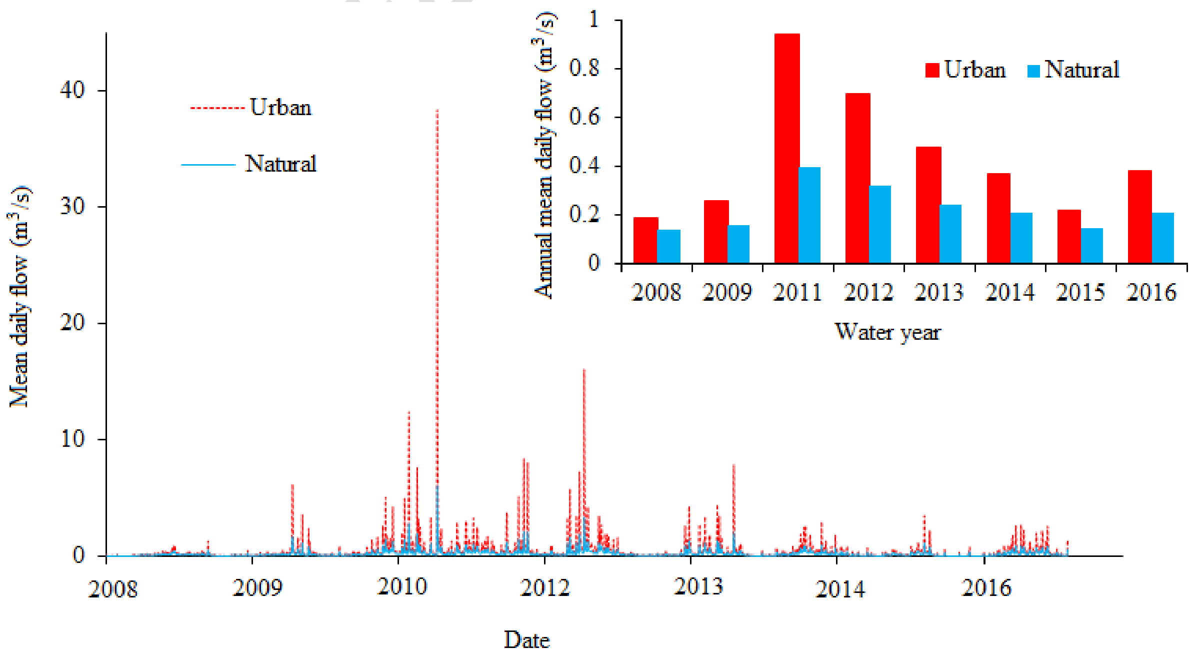

Figure 2. Daily flow hydrograph for the natural and urban reaches of the case-study catchment. Inset shows the annual mean daily flow for each water year.

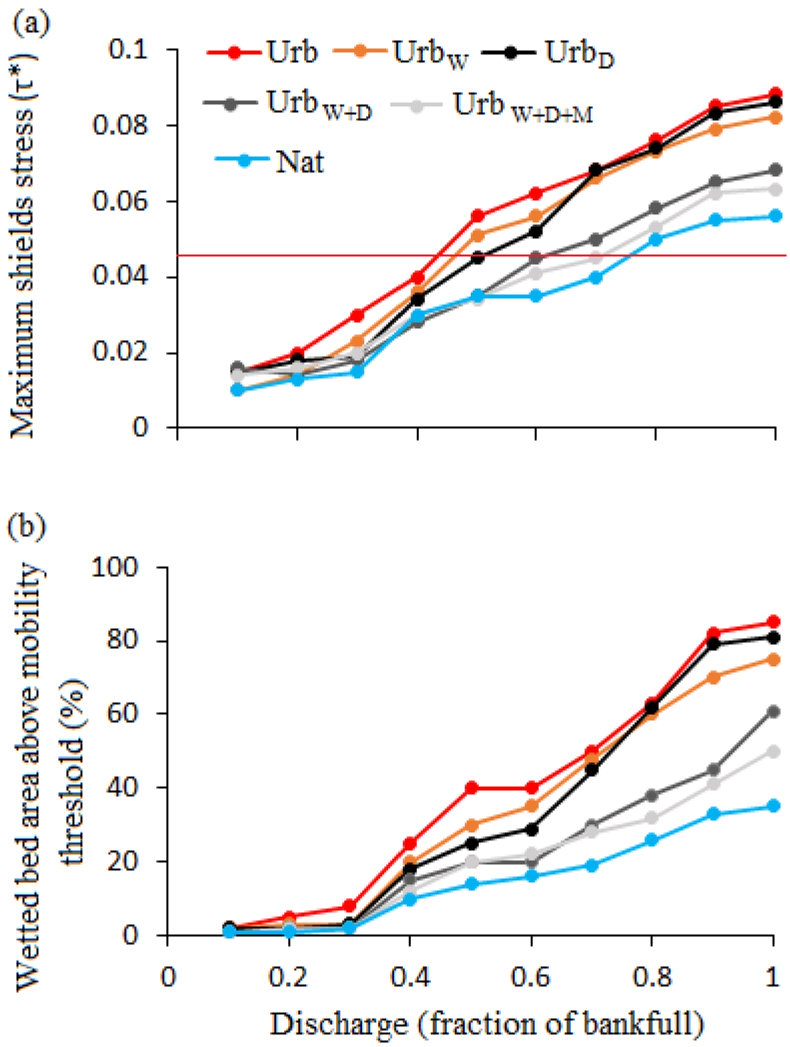

Figure 1. (a) Maximum (95th percentile) of bottom Shield stress and (b) percentage of wetted bed area above the critical mobility threshold ($\tau * > \tau_c^*$) with discharge (as a fraction of bankfull flow) for each channel configuration.

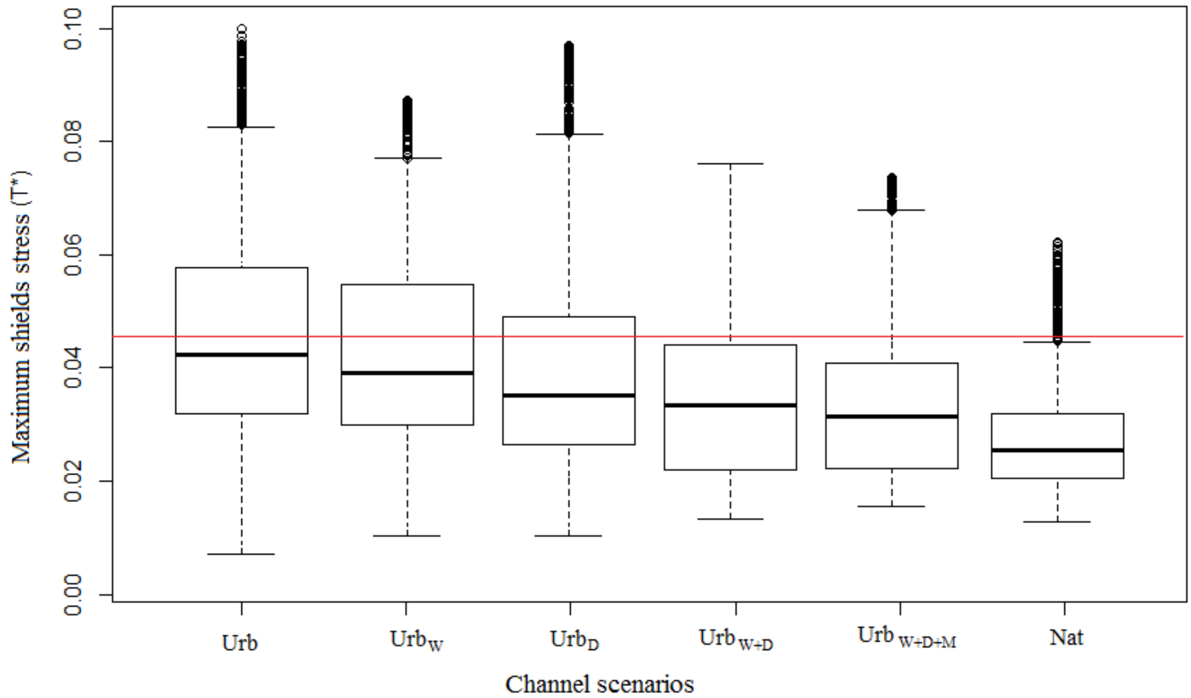

Figure 2. Box and whiskers plot of the distribution of daily maximum (95th percentile) Shield stress for each channel configuration.

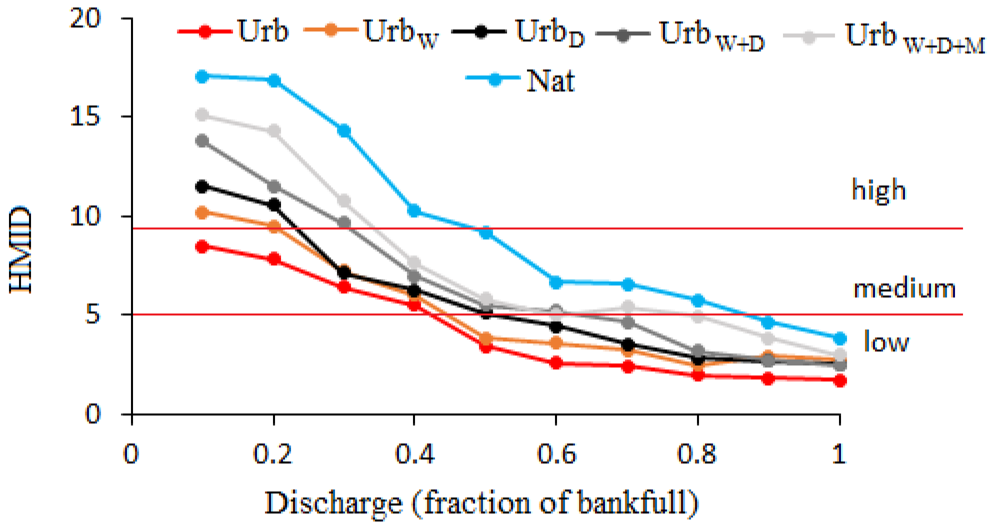

Figure 3. Hydro-morphological index of diversity (HMID) with discharge (as a fraction of bankfull flow) for each channel configuration. Red horizontal lines represent classified threshold defined by Gostner et al. (2013).

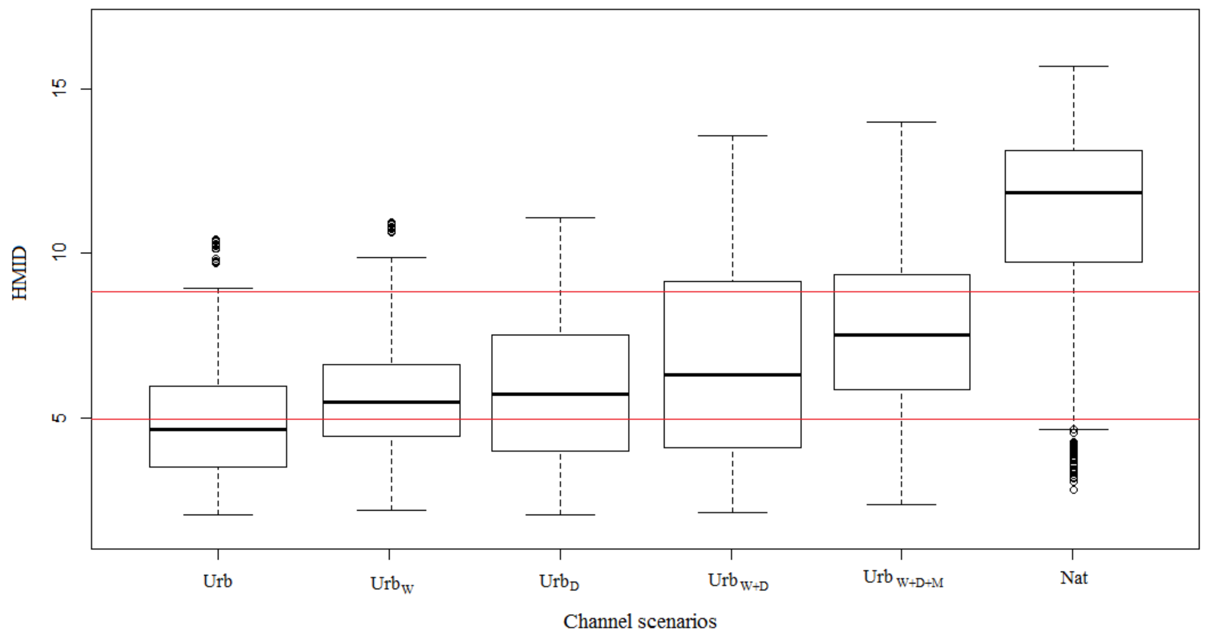

Figure 4. Box and whiskers plot of the distribution of daily HMID values for each channel configuration. Red horizontal lines represent classified threshold defined by Gostner et al. (2013).

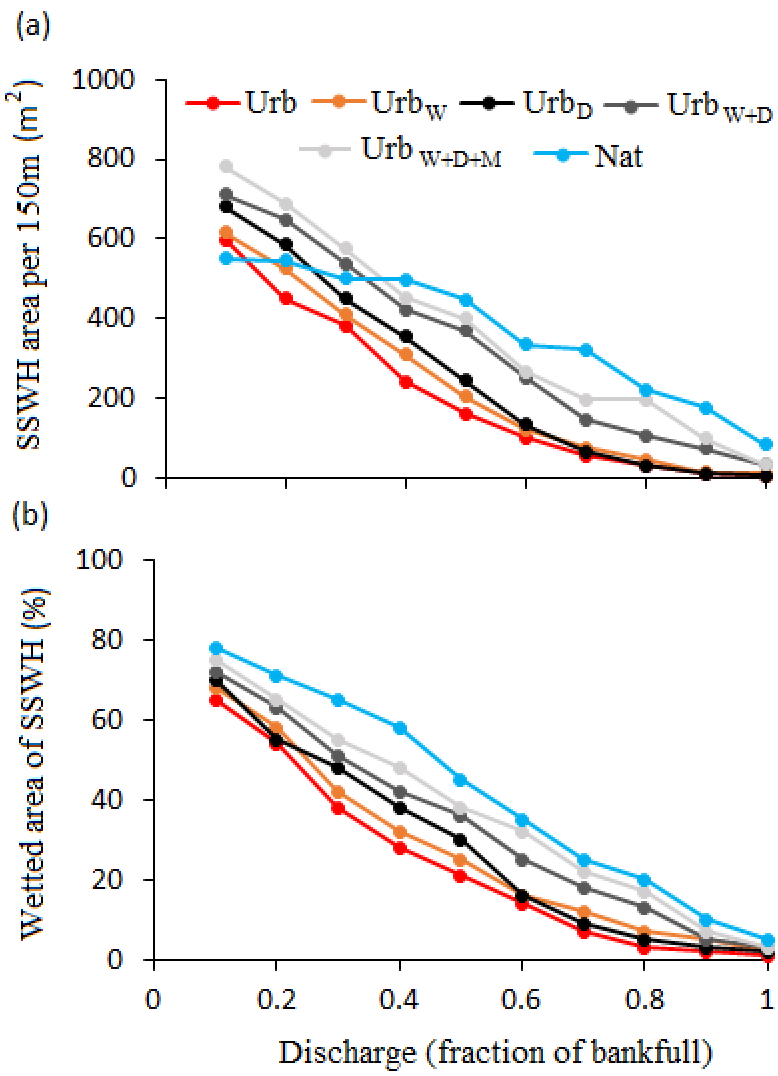

Figure 5. (a) Total SSWH area per 150m^2 (b) percentage of total wetted bed area that is SSWH with discharge (as a fraction of bankfull flow) for each channel configuration.

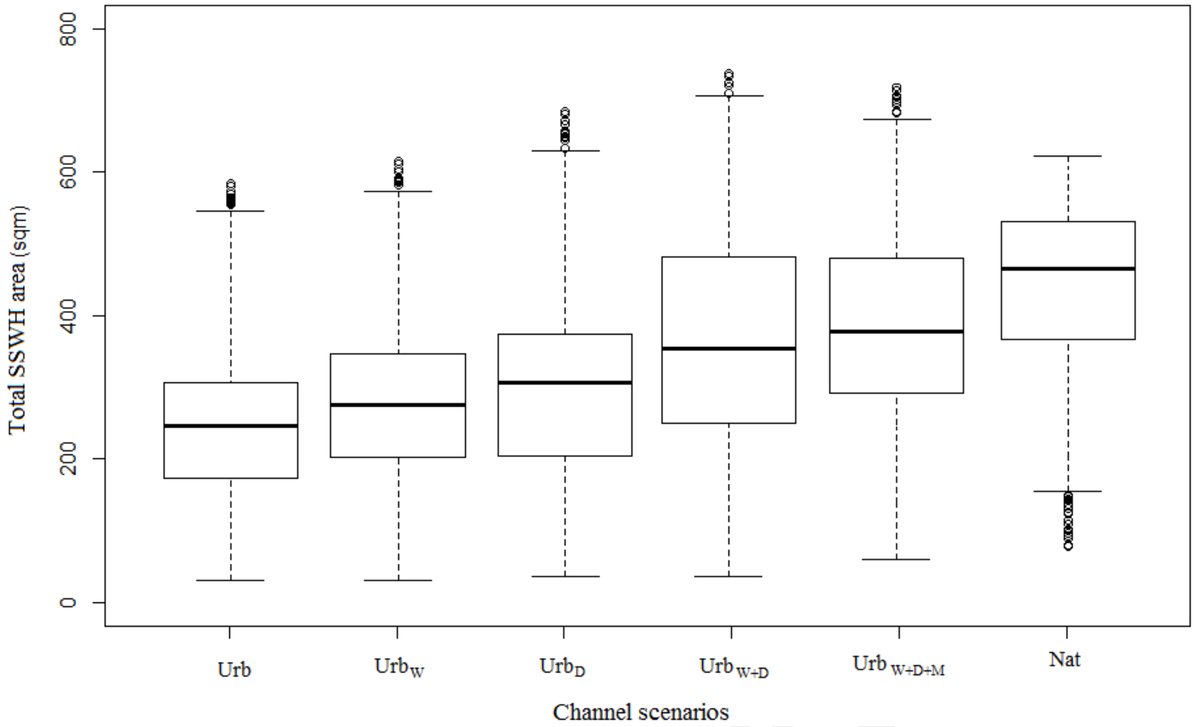

Figure 6. Box and whiskers plot of the distribution of daily total SSWH area for each channel configuration.